

# CP Violation and Dark Matter

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## Abstract

A brief review is given of the effects of CP violation on the direct detection of neutralinos in dark matter detectors. We first summarize the current developments using the cancellation mechanism which allows for the existence of large CP violating phases consistent with experimental limits on the electron and on the neutron electric dipole moments in a broad class of SUSY, string and D brane models. We then discuss their effects on the scattering of neutralinos from quarks and on the event rates. It is found that while CP effects on the event rates can be enormous such effects are reduced significantly with the imposition of the EDM constraints. However, even with the inclusion of the EDM constraints the effects are still very significant and should be included in a precision prediction of event rates in any SUSY, string or D brane model.

# 1 Introduction

SUSY/string models contain soft parameters which are in general complex and introduce new sources of CP violation regarding the electric dipole moment (EDM) of the electron and of the neutron. The typical size of these phases in O(1) and they pose a serious EDM problem. Thus the current limits on the electron[1] and the neutron[2] EDM are given by  $|d_e| < 4.3 \times 10^{-27}$  ecm,  $|d_n| < 6.3 \times 10^{-26}$  ecm and an order of magnitude analysis shows that the theoretical predictions with phases O(1) are already in excess of the experimental limits. For the minimal supergravity unified model (mSUGRA)[3] the soft SUSY breaking sector is characterized by the parameters  $m_0$ ,  $m_{1/2}$ ,  $A_0$  and  $\tan\beta$ , where  $m_0$  is the universal scalar mass,  $m_{1/2}$  is the universal gaugino mass,  $A_0$  is the universal trilinear coupling, and  $\tan\beta$  is defined by  $\tan\beta = \langle H_2 \rangle / \langle H_1 \rangle$  where  $H_2$  is the Higgs that gives mass to the up quark and  $H_1$  is the Higgs that gives mass to the down quark. In addition one has the Higgs mixing parameter  $\mu$  which is viewed as the same size as the soft SUSY parameters, and is determined by the constraints of radiative breaking of the electro-weak symmetry. In mSUGRA a set of field redefinitions shows that there are only two independent phases in the theory, and they can be chosen to be  $\alpha_{A_0}$  and  $\theta_\mu$  where  $\alpha_{A_0}$  is the phase of  $A_0$  and  $\theta_\mu$  is the phase of  $\mu$ .

The operators that contribute to the electric dipole moments consist of[4]

$$\begin{aligned} \mathcal{L}^{\mathcal{E}}_I &= -\frac{i}{2} d_f \bar{\psi} \sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu}, \quad \mathcal{L}^{\mathcal{C}}_I = -\frac{i}{2} \tilde{d}^C \bar{q} \sigma_{\mu\nu} \gamma_5 T^a q G^{\mu\nu a} \\ \mathcal{L}^{\mathcal{G}}_I &= -\frac{1}{6} \tilde{d}^G f_{\alpha\beta\gamma} G_{\alpha\mu\rho} G_{\beta\nu}^\rho G_{\gamma\lambda\sigma} \epsilon^{\mu\nu\lambda\sigma} \end{aligned} \quad (1)$$

Regarding the color dipole and the purely gluonic dimension six operator one uses the so called naive dimensional analysis[5]  $d_q^C = \frac{e}{4\pi} \tilde{d}_q^C \eta^C$ ,  $d^G = \frac{eM}{4\pi} \tilde{d}^G \eta^G$ , where  $\eta^C \approx \eta^G \sim 3.4$  and  $M = 1.19$  GeV is the chiral symmetry breaking scale. There are several solutions suggested to control the EDM problem. One possibility is that the phases could be small[6, 7], or there could be a mass suppression because of the largeness of the sparticle masses[8]. Recently, a new possibility was suggested, i.e., the cancellation mechanism[9] which can control the SUSY EDM problem and there have further developments[10, 11, 12, 13] and applications[14, 15, 16, 17]. The cancellation mechanism works in two stages. First one typically has a cancellation among the  $\tilde{g}$ ,  $\tilde{\chi}_i^\pm$ ,  $\tilde{\chi}_k^0$  exchange contributions to the EDMs. Second there are further cancellation among the electric dipole, the chromoelectric dipole and the purely gluonic contributions. Such cancellations are quite generic in a broad class of

SUSY/SUGRA[9, 10], and in string and D brane models[11, 12, 13]. In addition there are two loop contributions involving axionic Higgs exchange[18]. However, over most of the parameter space such contributions are relatively small.

While most of the analyses to explore the region of cancellations have been numerical in nature, recently there has been an attempt to explore the regions of cancellations also analytically[13]. Such a situation exists in the so called scaling region[19] where  $\mu^2/M_Z^2 \gg 1$  and one has  $m_{\chi_1} \rightarrow \tilde{m}_1, m_{\chi_2} \rightarrow \tilde{m}_2, m_{\chi_{3,4}} \rightarrow \mu$ . It was shown in Ref.[13] that in the scaling region one cancellation point in the  $m_0 - m_{\frac{1}{2}}$  plane can be promoted to a full trajectory where cancellations occur with only a minor adjustments of parameters. This promotion comes about via the following scaling on  $m_0, m_{\frac{1}{2}}$

$$m_0 \rightarrow \lambda m_0, m_{\frac{1}{2}} \rightarrow \lambda m_{\frac{1}{2}} \quad (2)$$

With the above scaling and under the constraint of the electro-weak symmetry breaking  $\mu$  undergoes the following transformation  $\mu \rightarrow \lambda\mu$  and the total electric dipole  $d_f$  transforms as  $d_f \rightarrow \lambda^{-2}d_f$ . Thus the point  $d_f = 0$  is invariant under  $\lambda$  scaling. Thus if cancellation holds at one point, it holds at other points under scaling by only a small adjustment of parameters and often with no adjustment of parameters at all. As discussed above in mSUGRA one has only two phases after field redefinitions. In the MSSM there are many more phases available[10]. A very general analysis shows that the electric dipole moment of the electron  $d_e$  depends on 3 phases, while the electric dipole moment of the neutron depends on 9 phases. Together  $d_e$  and  $d_n$  depend on 10 phases. The presence of many phases allows for cancellations in larger regions of the parameter space. A similar situation occurs in string and brane models[11, 12, 13]. Of course it may happen that certain models turn out to be free of the EDM problem as is the case in the work of Ref.[20] which also solves the strong CP problem. However, in general large CP phases could exist with a simultaneous resolution to the strong CP problem. For a recent discussion of the possibilities for the resolution of the strong CP problem see Ref.[21].

## 2 SUSY Dark Matter

There are 32 new particles in MSSM and any one of these particles could be an LSP. In SUGRA models, however, one finds that starting with prescribed boundary conditions at the GUT scale with gravity mediated breaking of supersymmetry one finds that the model predicts the lightest neutralino to be the LSP over most of the

parameter space of the model. Further, with R parity invariance the LSP will be stable and thus the lightest neutralino is predicted to be a candidate for cold dark matter over most of the parameter space in SUGRA models. Many analyses of supersymmetric dark matter already exist in the literature[22]. These include effects of FCNC constraints from  $b \rightarrow s + \gamma$ [23], the effects of non-universalities of scalar masses[24, 25], effects of non-universalities of gaugino masses[26, 27] and effects of co-annihilation[28]. Recently, effects of uncertainties in the WIMP velocity in the direct and in the indirect detection of dark matter have been analyzed[29, 30, 31] and analyses have also been given of the effects of uncertainties of the quark mass densities on the direct detection rates[32, 33, 27]. In this paper we discuss the effects of CP violation on direct detection.

### 3 CP Effects on Dark Matter

The effects of CP violation on the relic density have been discussed in Refs[34]. Here we discuss the effects of CP violation on event rates[35, 15]. The effective Lagrangian with CP violation is gotten from the microscopic SUGRA lagrangian by integration on the Z, Higgs, and sfermion poles and one finds[15]

$$\begin{aligned} \mathcal{L}_{eff} = & \bar{\chi}\gamma_\mu\gamma_5\chi\bar{q}\gamma^\mu(AP_L + BP_R)q + C\bar{\chi}\chi m_q\bar{q}q + D\bar{\chi}\gamma_5\chi m_q\bar{q}\gamma_5q \\ & + E\bar{\chi}i\gamma_5\chi m_q\bar{q}q + F\bar{\chi}\chi m_q\bar{q}i\gamma_5q \end{aligned} \quad (3)$$

Here A and B are spin dependent terms arising from the Z boson exchange and squark exchange and is given by[15]

$$A = \frac{g^2}{4M_W^2}[|X_{30}|^2 - |X_{40}|^2][T_{3q} - e_q\sin^2\theta_W] - \frac{|C_{qR}|^2}{4(M_{\tilde{q}1}^2 - M_\chi^2)} - \frac{|C'_{qR}|^2}{4(M_{\tilde{q}2}^2 - M_\chi^2)} \quad (4)$$

$$B = -\frac{g^2}{4M_W^2}[|X_{30}|^2 - |X_{40}|^2]e_q\sin^2\theta_W + \frac{|C_{qL}|^2}{4(M_{\tilde{q}1}^2 - M_\chi^2)} + \frac{|C'_{qL}|^2}{4(M_{\tilde{q}2}^2 - M_\chi^2)} \quad (5)$$

where  $C_{qR}$  etc are defined in Ref.[15] and  $X_{n0}$  give the gaugino-Higgsino content of the LSP and is defined by

$$\chi^0 = X_{10}^*\tilde{B} + X_{20}^*\tilde{W} + X_{30}^*\tilde{H}_1 + X_{40}^*\tilde{H}_2 \quad (6)$$

where  $\tilde{B}$  is the Bino,  $\tilde{W}$  is the neutral Wino, and  $\tilde{H}_1$  and  $\tilde{H}_2$  are the Higgsinos corresponding to the Higgs  $H_1$  and  $H_2$ . In Eq.(3) C governs the scalar interaction

which arises from the CP even Higgs exchange and from the sfermion exchange and gives rise to coherent scattering. It is given by[15]

$$C = C_{\tilde{f}} + C_{h^0} + C_{H^0} \quad (7)$$

where

$$C_{\tilde{f}}(u, d) = -\frac{1}{4m_q} \frac{1}{M_{\tilde{q}_1}^2 - M_\chi^2} \text{Re}[C_{qL} C_{qR}^*] - \frac{1}{4m_q} \frac{1}{M_{\tilde{q}_2}^2 - M_\chi^2} \text{Re}[C'_{qL} C_{qR}^*] \quad (8)$$

$$C_{h^0}(u, d) = -(+)\frac{g^2}{4M_W M_{h^0}^2} \frac{\cos \alpha (\sin \alpha)}{\sin \beta (\cos \beta)} \text{Re} \sigma \quad (9)$$

$$C_{H^0}(u, d) = \frac{g^2}{4M_W M_{H^0}^2} \frac{\sin \alpha (\cos \alpha)}{\sin \beta (\cos \beta)} \text{Re} \rho \quad (10)$$

In the above (u,d) exhibit the quark flavor in the scattering and  $\alpha$  stands for the Higgs mixing angle while  $\sigma$  and  $\rho$  are given by

$$\begin{aligned} \sigma &= X_{40}^* (X_{20}^* - \tan \theta_W X_{10}^*) \cos \alpha + X_{30}^* (X_{20}^* - \tan \theta_W X_{10}^*) \sin \alpha \\ \rho &= -X_{40}^* (X_{20}^* - \tan \theta_W X_{10}^*) \sin \alpha + X_{30}^* (X_{20}^* - \tan \theta_W X_{10}^*) \cos \alpha \end{aligned} \quad (11)$$

The D term in Eq.(3) arises from the exchange of the CP odd Higgs  $A^0$

$$D(u, d) = C_{\tilde{f}}(u, d) + \frac{g^2}{4M_W} \frac{\cot \beta (\tan \beta)}{m_{A^0}^2} \text{Re} \omega \quad (12)$$

while the terms E and F arise only in the presence of CP violation and are given by[15]

$$E(u, d) = T_{\tilde{f}}(u, d) + \frac{g^2}{4M_W} \left[ -(+)\frac{\cos \alpha (\sin \alpha)}{\sin \beta (\cos \beta)} \frac{\text{Im} \sigma}{m_{h^0}^2} + \frac{\sin \alpha (\cos \alpha)}{\sin \beta (\cos \beta)} \frac{\text{Im} \rho}{m_{H^0}^2} \right] \quad (13)$$

$$F(u, d) = T_{\tilde{f}}(u, d) + \frac{g^2}{4M_W} \frac{\cot \beta (\tan \beta)}{m_{A^0}^2} \text{Im} \omega \quad (14)$$

where  $\omega$  is given by

$$\omega = -X_{40}^* (X_{20}^* - \tan \theta_W X_{10}^*) \cos \beta + X_{30}^* (X_{20}^* - \tan \theta_W X_{10}^*) \sin \beta \quad (15)$$

and

$$T_{\tilde{f}}(q) = \frac{1}{4m_q} \frac{1}{M_{\tilde{q}_1}^2 - M_\chi^2} \text{Im}[C_{qL} C_{qR}^*] + \frac{1}{4m_q} \frac{1}{M_{\tilde{q}_2}^2 - M_\chi^2} \text{Im}[C'_{qL} C_{qR}^*] \quad (16)$$

In the limit when CP phases vanish, the above formulae limit correctly to previous analyses in the absence of CP phases. Numerical analysis shows that the coefficients A-F exhibit a strong dependence on CP phases. Typically, however, the terms D, E and F make only small contributions and the terms A, B and C generally dominate the scattering. The analysis of event rates follows the method of Ref.[36]. The analysis including the CP violating phases but without the imposition of the EDM constraints is displayed in Fig.1 where the ratio  $R/R(0)$  is plotted as a function of  $\theta_\mu$ , where  $R/R(0)$  is the ratio of the event rates with and without CP violation effects. The analysis shows that the CP violating phases can generate variations in the event rates up to 2-3 orders of magnitude. A similar analysis but with inclusion of the EDM constraints is given in Fig.2. Here one finds that the effects are much reduced[15], i.e., around a factor of 2 variation over the allowed range of phases. In Ref.[15] the analysis included only the two phases  $\alpha_{A0}$  and  $\theta_\mu$ . However, for nonminimal models we have three  $\xi$  phases in the gaugino mass sector. Only one of these three phases, i.e.  $\xi_1$ , enters the expressions of direct detection through the neutralino mass matrix. Among the remaining two phases,  $\xi_2$  affects the EDM of the electron and of the neutron while  $\xi_3$  affects only the EDM of the neutron. Using these differential effects generated by  $\xi_1$ ,  $\xi_2$  and  $\xi_3$  we can arrange cancellations for the EDMs to satisfy the EDM constraints and at the same time generate a large effect on the direct detection of neutralinos.

## 4 Conclusions

In a large class of SUSY, string and brane models there are new sources of CP violation arising from the soft breaking sector of the theory. Since the natural size of these CP phases is  $O(1)$  there exists a priori a serious EDM problem. The cancellation mechanism is a possible solution to the EDM problem with large CP phases. Detailed analyses show that there exists a significant part of the parameter space where large CP phases are compatible with the current experiment on the EDMs. The existence of large CP phases can have significant effects on low energy SUSY phenomenology, and in this paper we have discussed the effects of large CP phases on event rates in the direct detection of dark matter. We emphasize that the inclusion of CP phases in the dark matter analysis without the inclusion of EDM constraints can lead to erroneously large effects since the CP effects can change the event rates by several orders of magnitude. With the inclusion of the EDM constraints the CP effects are much smaller although still significant enough

to be included in any precision analysis of dark matter. These results are of import in view of the ongoing[37, 38, 39] and future[40] dark matter experiments. In addition to their effects on dark matter, large CP phases will also affect searches for SUSY at the Tevatron, at the LHC and in B physics and it is imperative that one include CP effects in future SUSY searches to cover the allowed parameter space of models. The cancellation mechanism is a testable idea. Thus if the cancellation idea is right, the EDMs of the electron and of the neutron should become visible with an order of magnitude improvement in experiment. Such a possibility exists with experiments underway to improve the sensitivity of the measurements on the electron and on the neutron electric dipole moments.

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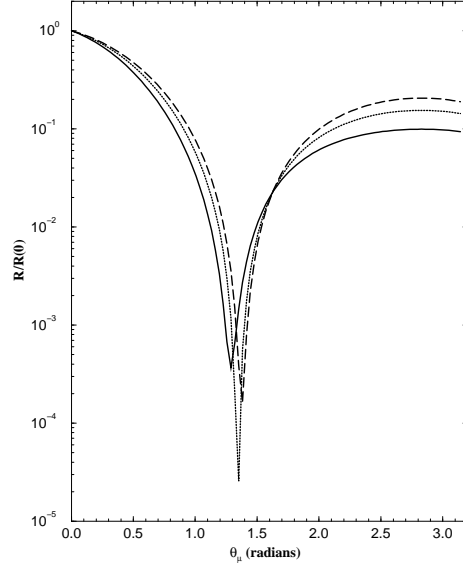


Figure 1: Plot of the ratio  $R/R(0)$  vs  $\theta_\mu$  without the imposition of the EDM constraints for three different inputs (From Chattopadhyay et.al. in Ref.[15]).

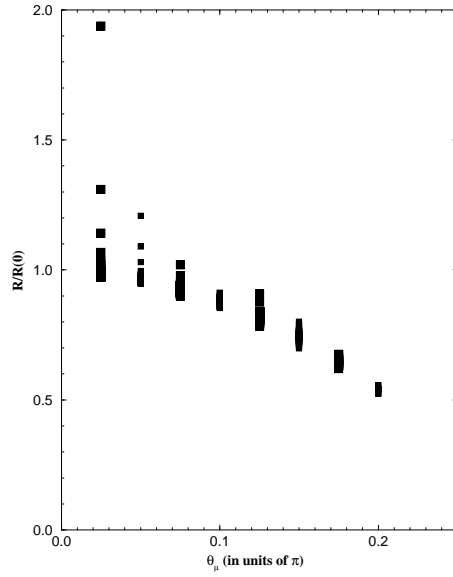


Figure 2: Scatter plot of the ratio  $R/R(0)$  vs  $\theta_\mu$  with inclusion of the EDM constraints (From Chattopadhyay et.al. in Ref.[15]).